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Spectral-Based Component of the Volume Sensor Program

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14. ABSTRACT

This report describes progress to date in the spectrally based component of the Volume Sensor (VS) Program at Naval Research Laboratory, in which the goal is to develop a remote, optical sensor for the detection of fire, smoke, and other hazardous events. Two distinct approaches to optical detection outside the visible are being pursued and the results to date are the subject of this report. These are long wavelength (near infrared), nightvision imaging and single or multiple element narrow spectral band optical detection at various wavelengths ranging from the mid infrared to the ultraviolet. As demonstrated in studies of small fires, long wavelength imaging provides high contrast for hot objects and more effective detection of reflected flame emission compared to visible video images. A spectral testbed, which consists of commercial optical flame detectors with diagnostic capabilities and single element detectors, has been constructed and its initial testing is described.

15. SUBJECT TERMS

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EXECUTIVE SUMMARY

This report describes progress to date in the spectrally based component of the Volume Sensor (VS) Program at Naval Research Laboratory. The goal of this program is to develop a remote, optical sensor for the detection of fire, smoke, and other hazardous events, such as flooding, inside ship spaces. It would also be advantageous to simultaneously provide surveillance capabilities.

A main component of the VS Program is to develop video detection in the visible region incorporating machine vision analysis of the images. To date this approach has been most successful for detecting smoke. The task of the spectral based component is to develop methods based on optical techniques in spectral regions outside the visible region, or otherwise using methods that emphasize spectral discrimination, to be used in conjunction with the visible machine vision techniques. The intention is to provide a more comprehensive overall volume sensor than would result from video detection alone. A major objective in this regard for the spectrally based component of the program is to be able to detect flaming and smoldering fires.

Two distinct approaches to optical detection outside the visible are being pursued and the results to date are the subject of this report. These are long wavelength, nightvision cameras, which provide some degree of both spatial and spectral resolution or discrimination, and single or multiple element narrow spectral band detectors, which are spectrally but not spatially resolved and operate with a wide field of view at various wavelengths ranging from the mid infrared to the ultraviolet. The primary advantage of long wavelength imaging is its higher contrast for hot objects and more effective detection of reflected flame emission compared to images obtained from cameras operating in the visible region. This is demonstrated in our studies of small fume hood fires. Several spectral element detectors have been designed primarily to detect narrow band emission due to atomic and molecular species such as sodium (589 nm), potassium (770 nm), and hydroxyl radical (308 nm) in addition to those commonly used in commercial flame detectors, i.e., IR (4.3 μm) and UV (185-260 nm). A spectral testbed has been constructed that is intended to be used to evaluate which detectors and which spectral bands are most effective for detecting fires in ship spaces. The tested configuration and initial testing is described. Both long wavelength cameras and the testbed will be further evaluated in tests to be conducted on the ex-USS *SHADWELL* and elsewhere.

SPECTRAL-BASED COMPONENT OF THE VOLUME SENSOR PROGRAM

INTRODUCTION

The Volume Sensor (VS) Program at NRL is part of the Advanced Damage Countermeasures Program in the Platform Protection Future Naval Capability. The goal of the VS is to use optical detection methods for remote and real-time monitoring of ship spaces, including but not limited to, detection of fire and smoke. Recent efforts have demonstrated significant improvements in accuracy and sensitivity in fire and smoke detection, such as multicriteria and early warning fire detection approaches that combine various sensors and utilize neural network algorithms [1,2,3,4]. The response time of these methods, however, are inherently limited by their reliance on point detection sensors (e.g., heat, smoke, or gases such as CO or CO_2), which depend on molecular or thermal diffusion from the fire or smoke source to the sensor. In principle, optical sensors can more quickly identify a fire or other hazardous conditions since they do not depend on diffusional processes but can obtain the relevant optical information nearly instantaneously (i.e., "at the speed of light," which would only take several nanoseconds in a ship compartment).

Optical detection is inherently rapid but also has the potential drawback that most optical methods are most effective when there is a direct line of sight (LOS) between the source and detector. Diffusion-limited point sensors are less affected by obstructions, so that, in principle, they provide better coverage albeit with slower response time. Under many practical circumstances, such as those in the cluttered environment of ship compartments, the LOS constraint may present a serious challenge to optical detection methods. It is probably not feasible to deploy enough sensors to provide complete direct LOS coverage for every area in the space. One possible solution is to detect reflected radiation as described below in the methods currently being explored.

The ideal optical approach might be to use thermal imaging with a mid infrared camera, by which we mean ones operating at wavelengths longer than 3 μm. Such cameras can directly detect the strong emission of fundamental vibrational bands of CO_2 (4.3 μm) and water (2.7 μm). This would be an approach that is both spatially and spectrally resolved. But mid IR cameras are too expensive for our intended application; they are several thousand dollars each and this is considerably more than is planned for implementing the VS for each ship compartment (<$100). Therefore, the program is divided into several efforts that can be ascribed to either spatially or spectrally resolved approaches.

The primary component of the VS program is concerned with pursuing the detection of fire, smoke, and other conditions using video fire detection in which the images are analyzed by machine vision algorithms. Video smoke detection systems have only recently appeared on the market. (One example is the Fire Sentry VSD-8.) These systems use video cameras operating in the visible and analyze the images using machine vision [5]. They are most effective at identifying smoke and are less successful at detecting flame, reflected or directly observed, or hot objects. Although there have been previous efforts in this area [6], existing methods do not appear to be suitable for US Navy ships as currently implemented. An evaluation of recently (or soon to be) marketed commercial machine vision systems has been recently reported [7]. Other approaches to machine vision detection are currently being pursued. Alternative sensor modalities are also being explored to be used in conjunction with image analysis. In particular, acoustic detection may be particularly useful for identifying events such as flooding.

The goal of the spectrally based volume sensor (SBVS) component is to develop methods for detecting fire, smoke, and other hazardous conditions using optical methods outside the visible region of

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the spectrum. This report describes recent progress in the SBVS effort. The sensors developed within the SBVS are intended to be used in conjunction with and to augment the video machine vision systems. The video detection systems are generally better at identifying smoke than fire, so a primary goal of the spectral component is to provide better detection for flame and fire. The video systems may also be susceptible to false alarms from nuisances, such as people walking into or through the field of view or personnel waving towels. The eventual goal is to send raw data from the spectral sensors along with the video input to the neural network for data fusion to provide a multicriteria optical sensor. In this context, single or multiple element flame detectors may optimize differently than if they were used as stand alone units.

Two main approaches are being explored outside the visible spectral region: nightvision or long wavelength imaging and single or multiple element sensors similar to those found in commercial-off-the-shelf (COTS) flame detectors. There has been progress to date in both approaches. Several series of videos have been recorded and show encouraging results. A testbed consisting of several sensors has been designed and configured, including the computer interface and development of a data collection program. Preliminary studies using the testbed were carried out for fume hood fires (paper, heptane, KCl in methanol). Other associated studies were also conducted, such as measuring UV/visible emission spectra for several fire sources to guide the spectral sensor wavelength selection. This work is in preparation for the CVNX and Volume Sensor 1 Test Series aboard the ex-USS *SHADWELL* in April, 2003.

BACKGROUND AND OPTICAL DETECTION STRATEGY

Spectral Regions

In order to clarify the following discussion on the spectral-based component of the VS program, we will define our terms for the spectral regions of the electromagnetic spectrum. The visible and UV regions are broadly recognized to be 400-650 nm and 180-400 nm, respectively. There is more confusion for the longer wavelength, infrared (IR) regions. There are different sub-regions of the infrared, in order of increasing wavelength, called the near infrared, mid infrared and far infrared. The most common boundary between the near and mid infrared regions is close to 3 microns. This roughly reflects the short wavelength edge of high transmission for standard optical materials, i.e., those commonly used in the visble region, such as silica and glasses. It is also the shortest wavelength for fundamental molecular vibrational bands. The entire range between 650 nm and 3000 nm is often called the near infrared region. For our discussion, it will be useful to distinguish wavelengths that are <1 μm from those that are > 1 μm. One micron is the cutoff wavelength for several detectors, such as charge-coupled devices (CCDs). For the purpose of our discussion, the term infrared (by itself) will refer to mid infrared radiation with wavelengths in the range 3-20 μm. The term near infrared will be used for the region 650-1000 nm unless otherwise specificied.

Long Wavelength, Nightvision Imaging

One approach we are pursuing is to use long wavelength or nightvision[1] videos. Nightvision video fire detection is a way to use both spectral and spatial information "on the cheap". Our approach exploits the long wavelength response (to about 1 micron) of standard, i.e., inexpensive, CCD arrays[2]

[1] Nightvision often implies a phosphor screen for visualizing NIR images (700-1000nm) in the region CCD cameras respond. There are several "generations" of this kind of nightvision viewer, often designated Gen I through Gen III; the higher number corresponds to more amplification of the image. We are using the term nightvision to indicate the NIR (<1 μm) spectral region.

[2] For example see the specifications for the Sony CCD array ILX554B.

used in many cameras (e.g., camcorders and surveillance cameras). This region is slightly to the red (700-1000 nm) of the ocular response (400-650 nm). A long pass filter transmits light with wavelengths longer than a cutoff, typically in the range 700-900 nm. This increases the contrast for fire, flame, and hot objects as well as suppressing the normal video images of the space, thereby effectively providing some degree of thermal imaging. There is more emission from hot objects in this spectral region than in the visible (<600 nm). One task is to establish the best filter to use for these videos. In addition, we acquired a near IR camera from (Electrophysics Model 7290A, 1.2-1.8 μm). A few example videos were collected with this device.

Long wavelength detection capability is now a standard feature on some camcorders (Nightshot^{TM} by Sony, MagicVu^{TM} by Panasonic) and is used extensively in surveillance "IR" cameras. Camcorders operated in normal mode use a short pass filter (near 650 nm) to block the longer wavelengths in order to color balance the videos toward the ocular response. In Nightshot mode, this filter is removed so that the longer wavelength CCD response can be utilized to "see in the dark". The surveillance cameras are widely marketed for security and are often sold with an IR (near 850 nm) illuminator to increase visibility in the dark. We also plan to explore using an illuminator for tasks such as controlling light levels in video monitoring. The surveillance cameras are widely available and very inexpensive (<$100) so that this is an approach that is genuinely economical.

This is the first use of nightvision videos for indoor fire detection to our knowledge. The approach is a compromise between expensive, spectrally discriminating cameras operating in the mid IR and inexpensive, thermally indifferent visible cameras. We suggested the general notion of finding a compromise between spectral discrimination or thermal contrast (in the mid IR) and cost (in the visible) in our 2001 literature survey [8], in which we mentioned a middle ground may be to use nightvision and near infrared cameras [9]. Longwave or near IR emission radiation detectors have been used before for fire detection. These utilize either several narrow band detectors (without imaging) or near infrared cameras. The former approach has been reported and patented by Lloyd et al. [10,11,12] in which two NIR detectors were used (at 900 and 1000 nm) and time series and Discreet Probability Function numerical analyses were applied. The results showed that the apparent source temperature was different for direct and reflected radiation from a hot emission source (flaming or smoldering). This work demonstrated the feasibility of detecting reflected near IR light, which as stated above, is important for achieving comprehensive detection coverage for an optical detection method. Since the approach does not include imaging, it is not as successful as our approach at discriminating between real fires and false alarms or at identifying the nature of the source emission that is presumably hot. In addition, near IR image detection has been applied in background free environments, such as for monitoring forest fires from terrestrial based [13] and satellite images [14], tunnels [15], as well as aircraft cargo surveillance [16]. The latter study includes a detailed characterization of using CCD cameras in the NIR for remote temperature measurement (for >350 C). Near IR detection of forest fires is effective in part because there are few if any interferences or nuisances to complicate the detection. Outdoor imaging typically uses wavelengths longer than 1 micron. We have used shorter wavelengths for imaging, 700 to 1000 nm, in order to prevent the method from being too expensive to implement in each ship compartment. We anticipate nightvision videos to be particularly beneficial in several respects: providing high contrast and therefore straightforward LOS detection for flames and hot objects, where the latter would include bulkheads that have been heated by obstructed fires and identifying obstructed fire and flame based on reflected light.

Nightvision videos with various long pass filters were recorded (using both a Sony camcorder in Nightshot mode and inexpensive "bullet" cameras) for several hood fires at NRL as well as for preliminary studies of the sources planned for the ex-USS *SHADWELL* Volume Sensor 1 Test Series.

Single/Multiple Element Spectral Detection

The second approach to an optical detector being investigated utilizes a single (or few) element(s) with a wide field of view that responds within a narrow spectral region corresponding to emitted radiation that eminates from a flame. There are two elements to our single/multiple element approach. One involves using COTS flame detectors that incorporate a serial diagnostic output to provide raw data from each sensor. This permits each sensor element to be evaluated independently from the overall operation of the unit for use within the VS to augment the video detection. We also assembled our own, in-house sensors using commercially available detectors and interference filters. These include several that closely resemble those in flame detectors, specifically in the mid IR and deep UV spectral regions, as well as some to detect at wavelengths not commonly found in commercial systems. The latter are based on atomic (sodium, 589 nm; potassium, 766 nm) and molecular (hydroxyl radical, 308 nm) emissions that have been observed (by us and others) in emission spectra of flames.

The single/multiple element detection approach is used in commercial optical flame detectors (OFD). These devices sense emitted radiation in narrow spectral regions where flames emit strongly. The most prevalent is the mid infrared region, particularly at 4.3 μm, where there is strong emission from CO_2. The 4.3 μm band emission is from the asymmetric stretching band of CO_2; which has a very high absorption bandstrength of about 2000 $cm^{-2}atm^{-1}$, which is about ten times stronger than the fundamental band of carbon monoxide. COTS OFDs can now detect 2 or 3 bands simultaneously, including other IR wavelengths and/or in the UV. The detection effectiveness depends on both the strength of the emission and the detector sensitivity. The strongest emission is in the IR, which compensates for the relatively insensitive available IR detectors. UV detectors, such as UV tubes used in OFDs, are typically very sensitive; this compensates for the relatively weak UV emission from fires. The wavelengths utilized are chosen for the specific application to increase sensitivity and minimize false alarms; they often operate in both the UV and the IR or at as many as three IR wavelengths. There is an emerging trend to also include a broadband IR element, e.g., 1-5 μm, as well. Some of the COTS detectors also use some time dependent signal criteria such as flicker rate or signal rise time, as well as absolute signal levels for identifying a fire condition. A popular application for OFDs is in aircraft hangar bays. About 5 years ago, Gott et al. reported a study that concluded that of the detectors evaluated, UV/IR OFDs were the most effective for hangar bay fire detection [17]. Subsequently, a study by Gottuk et al. on OFD performance in aircraft hangars found that triple IR detectors were more effective than units using UV/IR and dual IR [18]. This provided evidence that the Navy regulation stipulating that the hangar fire detectors use UV/IR was unwarranted. The current practice in the Navy hangars is now to use triple IR OFDs. OFDs are effective at monitoring a wide area, but they are flame detectors and not very sensitive for smoldering fires. This may complement the capability of video detection for identifying smoke, such that an OFD/video detection system may provide a comprehensive monitor for both flame and smoke. A limitation to OFDs, however, may be that they are LOS-limited so that they would not respond quickly to an obscured event.

For the first element of the testbed, we sought COTS OFDs that would allow us to monitor the raw data from each sensor element in order to determine whether it would be beneficial to utilize that particular sensor element/spectral in the VS. After surveying the available COTS OFDs, we found two units capable of providing the desired diagnostic outputs for continuously monitoring each sensor element. These are both UV/IR OFDs, detecting the ~4 μm band in the IR and using a UV tube (185-260 nm). One is the Ominguard 860 from Vibrometer and the other is the EyeSpy 502 from Fire Combat (now sold through Sensor Electronics). As a result of considerable cooperation from both vendors, including some EPROM modifications for the Omniguard and data translation information from Fire Combat, these devices now provide continuous serial diagnostics for each sensor element.

The second type of testbed sensors are constructed in-house for narrow spectral bands that correspond to atomic or molecular emission. These span a wide spectral region including IR, visible and UV. Hydroxyl radical, OH, is well known to be prevalent in flames and it emits near 308 nm. An OH detector was constructed using a photomultiplier tube (PMT) and a 310 nm interference filter. As indicated below, this emission is relatively weak and was not observed with the CCD array spectrometer detected flame emission spectra but could be seen with the filtered PMT.

We are also pursuing structured emission lines in the visible region that appear primarily due to the presence of salts in many fuel sources, especially for class A fires. Atomic emission of potassium has recently been reported as a way to identify fire in remote, satellite detection [19]. Potassium atoms emission due to the $^2P_{3/2}$–$^2S_{1/2}$ and $^2P_{1/2}$–$^2S_{1/2}$ transitions occur at 766.5nm and 769.9nm, respectively. In remote sensing, long pathlengths are involved. Singlet oxygen absorption lines fall in this region and nearly interfere with the potassium emission. For our purposes, the pathlengths are short so that oxygen absorption is not an issue. Similarly, the spectra we have recorded for fires indicate that emission from sodium (at 589 nm) is usually even stronger than from potassium, so we are exploring this band for optical detection. Implementing detection of these optical emission bands will include another channel in a nearby guard band to minimize false alarms. It is noted that there may be numerous possible interferences with the sodium lines, such as from compartment lighting.

METHODS AND RESULTS

Long Wavelength, Nightvision Imaging

The results to date for the long wavelength, nightvision video fire detection effort are several series of nightvision videos of various small fires. In several cases, videos were obtained in parallel with the initial evaluation of one or several sensors that comprise the spectral testbed. The long term plan for the videos is to incorporate a computer-based algorithm to automate analysis of the videos for the presence of fire or flame and hopefully smoke. Machine vision algorithm development is being pursued by others in the Volume Sensor Program and through cooperative agreements with various companies. There is an agreement in place with Fastcom Technologies, whose video smoke detection system (Smoke and Fire Alert (SFA) System) is being evaluated within the VS Program. The progress to date includes recording videos with different filters to demonstrate the advantages of using cameras operating at wavelengths slightly longer than the visual range without an automated detection capability.

An important task within this element is the digitizing and archiving of test videos in such a manner that is expedient and in an appropriate format such that they can be used for algorithm development (present and future). It would be best if they could be digitized in real time. An approach to achieving this has been identified and is being implemented. More details about the video digitization issue, which pertain to both the video and nightvision videos, will appear in an upcoming report [20].

Nightvision videos of various fires were recorded using either a Sony DCR-TRV 27 camcorder in Nightshot mode or a surveillance, bullet camera (obtained from 123security.com, shown in Figure 1). In each case various long pass filters were used. These were typically 720, 850, 925, and 1050 nm. There are commercially available long pass filters with 720 nm (e.g., Hoya R72) and 900 nm (Hoya RM90) cutoffs that can be directly attached to the front of the camcorder. For the bullet cameras, a filter mounting adapter was designed and fabricated to house 2 inch square color filters that are used, such as those from Schott or Corning.

Several series of videos were recorded:

- preliminary studies of hood fires - heptane, paper, and smoke pellets; fires for initial tests of spectral testbed – heptane, paper, KCl/methanol;
- fire and smoke sources planned for Volume Sensor 1 Test Series on ex-USS *SHADWELL*, April 2003 including: cardboard, heated cable, potassium chloride/lactose;
- filter series, in which paper and heptane fires were recorded using various filters in Nightshot as well as in normal video mode;
- candle and KCl/methanol with various filters – in conjunction with potassium (770 nm) photodiode spectral detector.

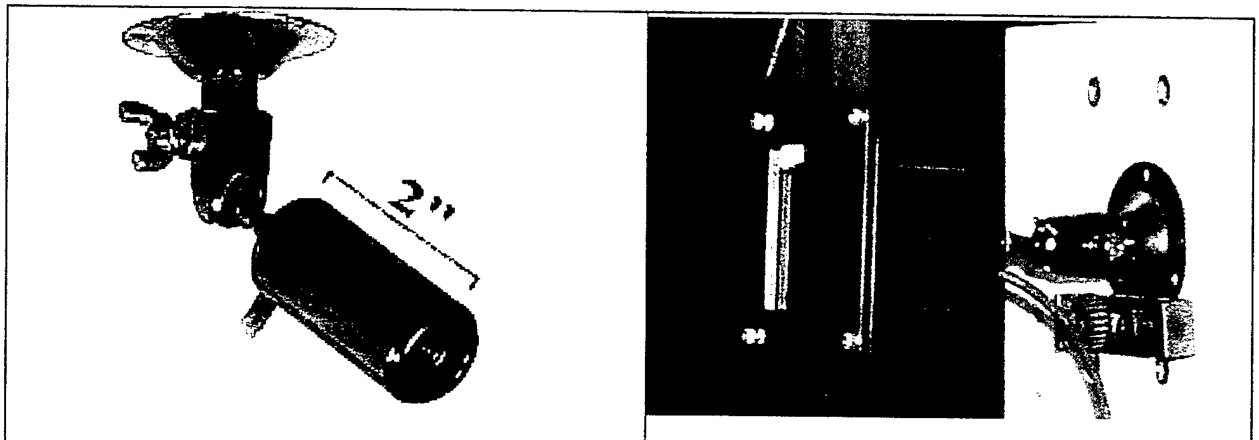

Figure 1. Bullet camera used for nightvision videos shown both with (right) and without (left) long pass filter attached

Even without using a long wavelength filter, the initial video recorded in Nightshot showed that utilizing the deep red response of the CCD accentuates the appearance of flame and fire emission compared to the intensity of the surrounding image. It was rapidly determined that the contrast for flame and fire can be significantly increased by using a long pass filter. When the videos are more heavily filtered, where in this case heavily refers to longer cutoff wavelength, it suppresses the room temperature, normal image of the surroundings and increases the discrimination for flame emission. For relatively light filtering, the image of the surroundings are visible but more faint, and of course the thermal contrast is not as high as with heavier filtering. The primary advantages of greater emission discrimination is the ability to see reflected light and hot objects. The optimal degree of filtering depends on the application, such as the details of the space being monitored and whether the camera will be used as a stand alone device or in combination with video camera or other sensors. Images that are nearly zero background, i.e., in which the only events observed are hot objects, should simplify using computer analyses to determine the presence of fire and smoke; the event discrimination capability is achieved more by the hardware (camera) than the software. Extracted images from several videos are shown to illustrate the findings.

The ability to provide high thermal contrast is demonstrated in the extracted images from videos for a cardboard fire recorded in normal mode (unfiltered) and in Nightshot mode using a 720 nm long pass filter, as shown in Figures 2 and 3, respectively. This video was recorded in preliminary studies of fires planned for the Volume Sensor 1 Test Series. In normal mode, as in Figure 2, it is not clear that the smoldering embers are warmer than the surroundings. In contrast, in the filtered nightvision image, surroundings are only faintly visible but the hot center portion of the picture is brighter, so that it is more evident that the ashes of the paper that was just burned are significantly hotter than the other objects within the field of view. In several tests, it was evident that nightvision videos are better for identifying

hot objects than normal video. There were repeated instances after burning paper that the ashes could be identified as hot in nightvision but not in regular video. Similar results were observed in another Volume Sensor 1 Test Series fire in which a bundle of cables was heated with a resistive heater. They smolder and eventually ignite. In the filtered nightvision videos, it was possible to detect the heater element "glowing" before there was any noticeable smoke or fire and before there was any indication of heating in the normal mode video. The effect of using long pass filters both with and without using Nightshot mode is demonstrated in the extracted images from a series of videos for a paper fire as shown in Figures 4-6. Figure 4 was recorded in regular mode; the fire is evident, but the surrounding image has several objects that are visible, including the bright reflected light from the bottom front of the hood that has a similar color as the flame. In Figure 5, the 720 nm filter has been placed in front of the camera, which is still operating in normal mode. In Figure 6, the emission from the flame is significantly brighter with the camera's Nightshot mode turned on. In fact it is possible to see the reflected emission behind the flame, which is not evident in the other two images. This shows that the higher contrast for flame emission in filtered nightvision videos increases the likelihood of detecting reflected light from fires. Nightvision videos provide an enhanced capability to detect reflected emission from fires. This is easier to see in videos than in extracted images since a characteristic property of the reflected light is the synchronous flicker observed from several positions. Figure 7 shows several images from a series of videos recorded for a pair of fires next to each other. The fuel for the fire on the left is methanol saturated with potassium chloride and a candle is burning on the right. The former gives a strong potassium emission (near 770 nm) and was used to evaluate the narrow band, single element sensor intended to detect this line. In the unfiltered videos, in both normal and Nightshot modes, the methanol flame is difficult to see.

The filtered Nightshot images clearly suppress the surrounding images so that all that is visible are the flames from the fires. The methanol/KCl emission is strongest near 770 nm, so that its flame is more easily seen with the shorter wavelength 720 nm filter that passes the potassium line. The 830 nm filter blocks much of the potassium emission so that candle flame appears brighter in this case. This suggests that if the anticipated fires are expected to have a significant potassium emission, the long pass filter should be short enough to pass the potassium emission, i.e., 750 nm or shorter.

The initial studies consisting of videos of fires recorded with long wavelength cameras demonstrate that this is a promising route for improved discrimination of hot objects and reflected radiation compared to video detection in the visible region. We anticipate that the advantages of this approach will be more clearly established in the Volume Sensor Test Series on the ex-USS *SHADWELL*.

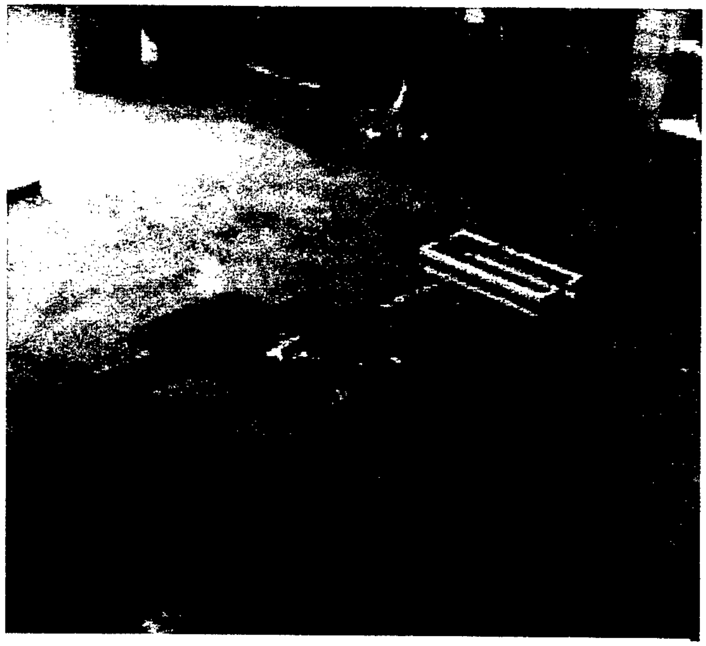

Figure 2. Late in cardboard fire recorded in normal mode

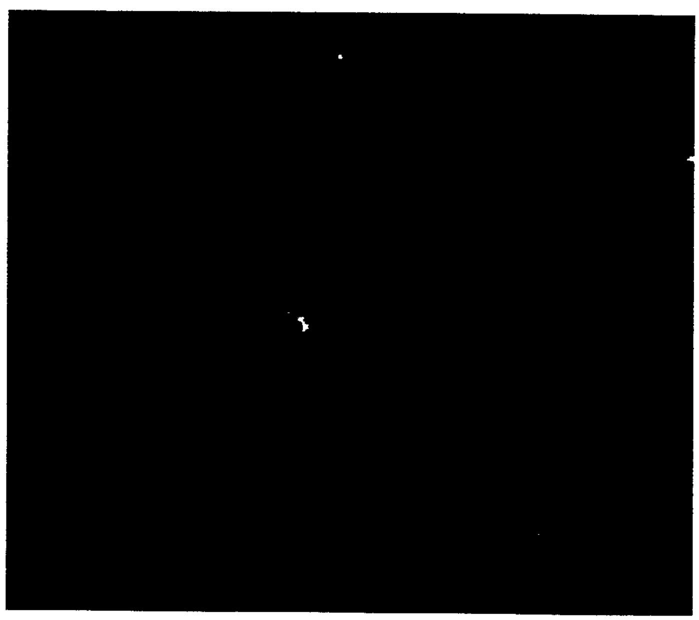

Figure 3. Late in cardboard fire recorded in Nightshot mode with a 720 nm long pass filter

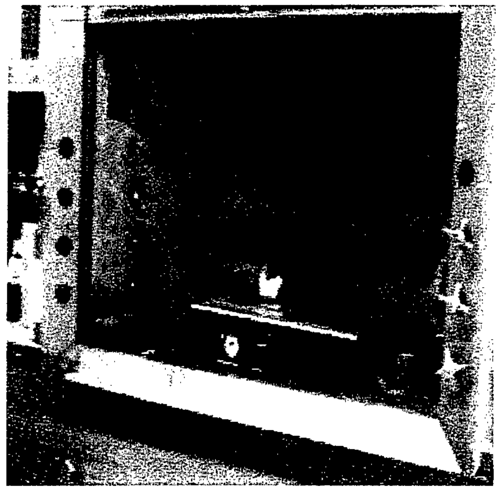

Figure 4. Paper fire in regular mode without any filters

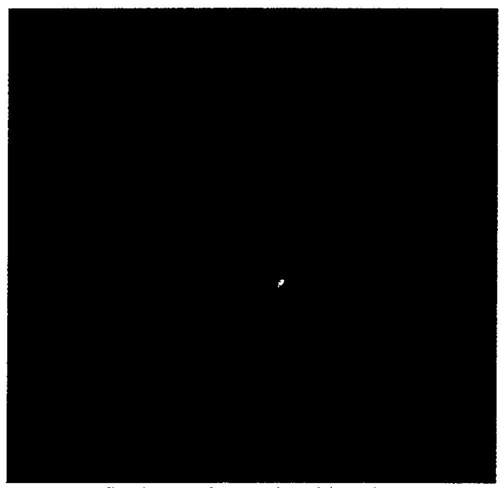

Figure 5. Paper fire in regular mode with 720 nm long pass filter

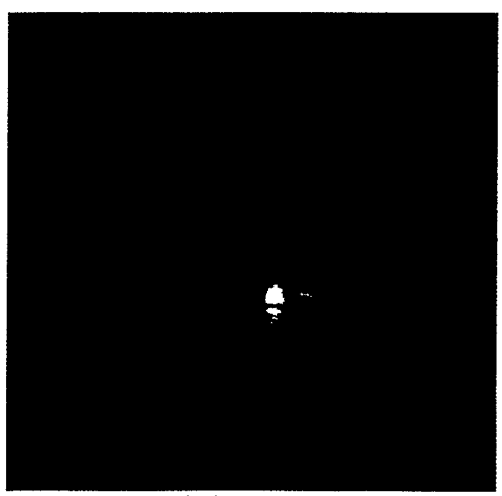

Figure 6. Paper fire in Nightshot mode with 720 nm long pass filter

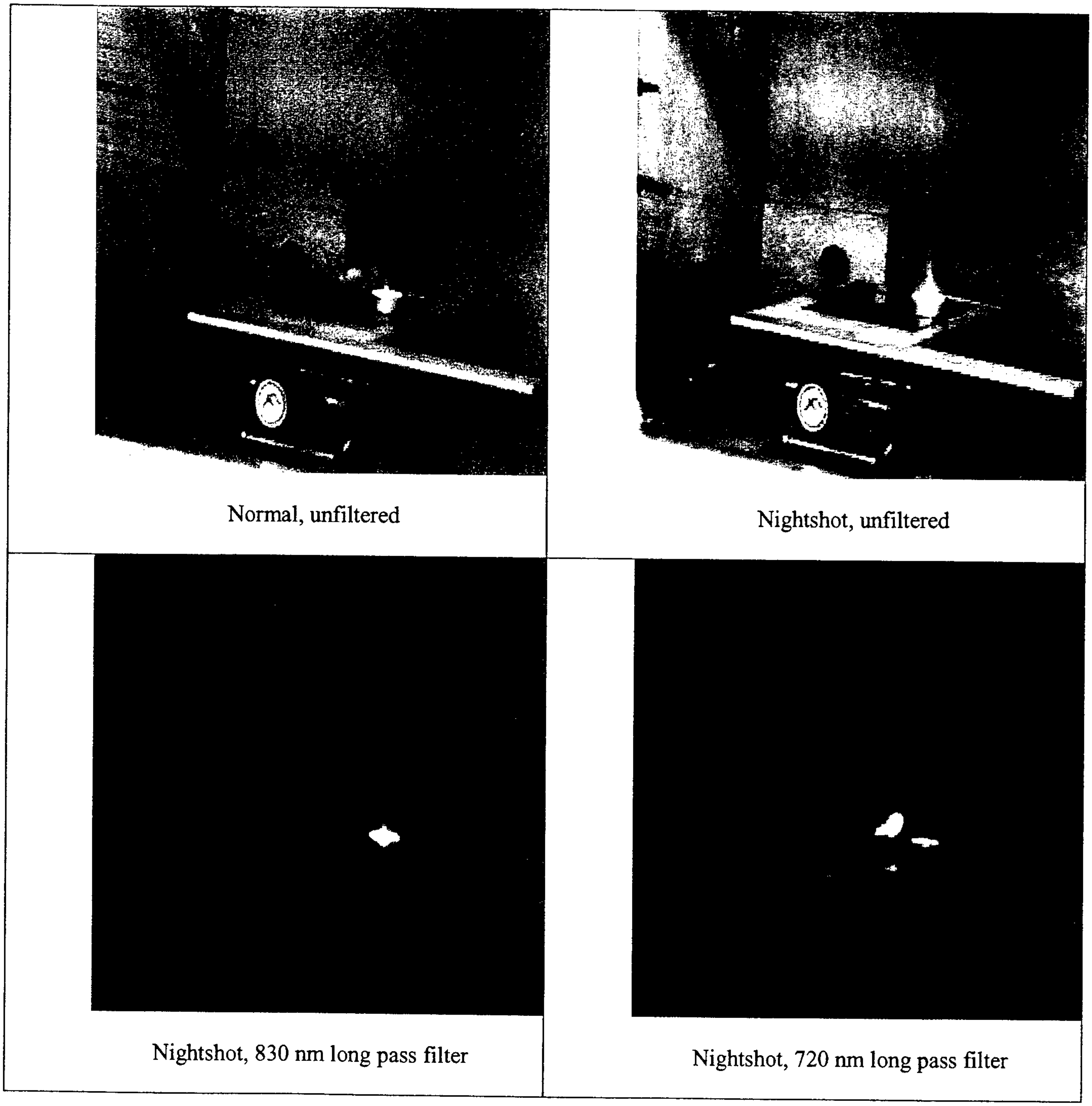

Figure 7. Side-by-side fires of methanol with KCl (left) and a candle (right) recorded under various conditions as labeled

Single/Multiple Spectral Sensors

UV/Visible Emission Spectra of Fires

In order to determine the most effective spectral regions to use for single/multiple element detection, UV/visible emission spectra were recorded for several fires. The spectra were obtained with fiber coupled spectrometers; the Ocean Optics Model USB2000 (200-900 nm range) and the Spectral Instruments Model 420 (200-950 nm range). The former is more portable and somewhat more sensitive

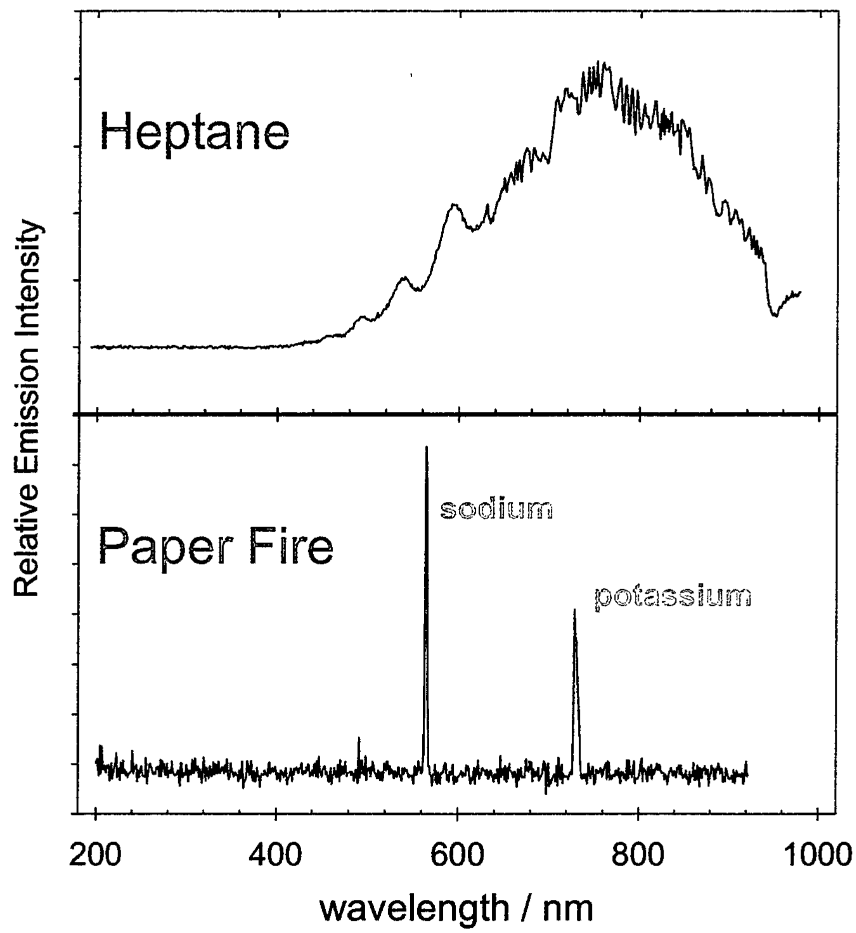

Figure 8. UV/visible emission spectra measured for hood fires using fiber coupled array spectrometer. Upper panel:heptane fire; lower panel: paper fire

while the latter operates out to slightly longer wavelengths. A pair of emission spectra shown in Figure 8 was collected for two fume hood fires. The upper panel shows the spectrum measured for a heptane fire. In this case the emission is broad and featureless. The structure observed is probably due primarily to the wavelength variations in the CCD array sensitivity rather than the flame emission. The lower panel shows the spectrum obtained during the course of a paper fire. In contrast to the heptane fire, the paper fire spectrum exhibits very sharp bands that are due to atomic emission of sodium (at 589 nm) and potassium (near 770 nm). The results for the paper fire encouraged us to adapt the previously demonstrated approach of using potassium emission as one of our sensors in the spectral testbed.

Despite several attempts, we were unable to detect hydroxyl radical emission near 310 nm, which we were hoping to observe due to hydroxyl radicals. We were able to see fire emission in this region using a more sensitive detection arrangement comprised of an interference filter and a photomultiplier tube (PMT). Emission spectra were also measured for the fires planned for the Volume Sensor 1 Test Series and the results are shown in Figure 9. The fires are heated bundles of cable, cardboard, and a chemical mixture intended as a smoke source. The spectrum of the heated cable bundles are broad and without any narrow features (this was taken when the cables were ignited not just smoldering). There is a significant 589 nm sodium emission and much weaker 770 nm emission from the cardboard fire. When ignited, the potassium chlorate/lactose burns brightly in manner that resembles sparkler. Since there is a high fraction of potassium in the mixture, it is no surprise that there is a strong emission at the potassium line. This is a somewhat artificial result since most fire sources will not have this high a percentage of potassium.

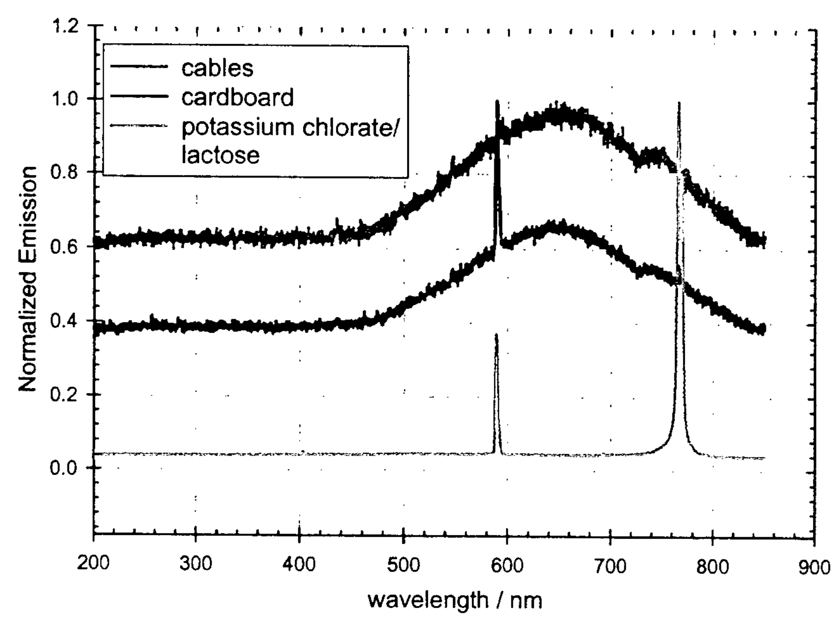

Figure 9. Emission spectra measured for fires planned for the Volume Sensor 1 Test Series

Testbed Configuration

The strategy and general description of the narrow band spectral sensors that comprise the testbed have been related above. Table 1 lists hardware details for each sensor element, including the spectral wavelength of detection, which is determined by the interference filter and the kind of detector. The UV

tubes are inherently sensitive only to UV radiation (185-260 nm), so that they require no interference filter to be spectrally specific. Table 1 also lists the detector elements/spectral bands for the two flame detectors, which are equipped with serial diagnostic outputs that provide raw data for each detector. The Ominguard has one 4.4 µm IR element and an Edison tube. In addition to these outputs, the serial data provides an additional "fire data" value, that is a propriety quantity based on both the IR and UV signals and is used to determine the alarm condition. The Eyespy consists of four detector elements: two narrowband (4.3 µm) detectors, one aimed to the right and the other to the left; one broadband IR (1-5 µm) and a UVTron tube. The alarm condition is independent of the broadband output; it depends on the UV and either narrowband IR. In addition to the two OFDs with serial diagnostic outputs, another UV/IR OFD (Det-tronics U7652B) was also used to monitor the test fires. This unit was not deployed for the ex-USS *SHADWELL* test because other OFDs (Omniguard 752, also without serial diagnostics) were already installed.

The in-house mid-IR detector initially tested was a liquid nitrogen cooled mercury-cadmium-telluride detector (MCT, IR Associates, 2 mm square, model MCT-13-20 with attached preamplifier). Later a room temperature PbSe (Judson Technologies J14TO Series, 1x1 mm, Model PE-0-51) was used with a 90 V DC bias. The IR detectors are AC coupled, so a mechanical chopper was sometimes used in front of the detector. Since the emission varies over time due to flicker, the excursions of the unchopped signal were not much less than those for the chopped signal. We obtained and initially tested our own UVTron tube in addition to the ones in the OFDs but found it to be redundant and somewhat less sensitive than the UV tubes in the Omniguard and Eyespy OFDs, so it will not be included in the configuration to be used in the upcoming ex-USS *SHADWELL* tests. Photodiodes were used for narrow band NIR and visible (potassium, sodium and guard bands) detectors. A photomultiplier with an 310 nm interference filter was used to detect emission from OH.

Table 1. Sensors included in the spectral testbed

Sensor		Element/Detector or Relay	Spectral Region/ Interference Filter (IF)	Output
COTS flame detectors				
Omniguard 860		Infrared (Ref IR)	4.4 µm IF	Serial
		UV (Edison tube)	185-260 nm	Serial
		Fire IR	4.3 µm IF	Serial
		Alarm and Fault Relays		Digital
FireCombat EyeSpy 502		IR x 3 (DC and AC)	2 x 4.3 µm IF (left and right); broad (1-5 µm)	Serial
		UV (UVtron)	185-260 nm	Serial
		Alarm and Fault Relays		Digital
Det-tronics U7652B		Alarm and Fault Relays		Digital
		IR/UV Relay	N/A	Digital
In-House				
UV	BB UV	UVTron	185-260 nm	Frequency
	OH radical	Photomulitplier	308 nm IF	Analog
Visible	Potassium	Photodiodes (UDT)	589 nm IF	
	Sodium		766 nm IF	
	Guard		1050 nm IF	
IR	CO_2	MCT (LN_2)	4.3 µm IF	
		PbSe (RT)		

All single-element detector outputs as well as the relay outputs from the OFDs were connected to a PC-based data acquisition card (DAQ, National Instruments, PCI-6036). All data were logged and time-stamped to the nearest millisecond by a custom Visual Basic data logging program called DataLogger developed by NRL's Code 6111. All inputs to the DAQ are polled at 10 Hz and collectively stored to a text file. There is a provision in place for polling the frequency inputs of the DAQ at integral divisors of 10 Hz for low-count rate sources. The Omniguard diagnostic output data is received by the PC via an RS-485 interface card (National Instruments, PCI-485I) at 1 Hz. The program writes each Omniguard data packet with a time stamp as received to a separate text file. The EyeSpy diagnostic outputs are polled at 1 Hz and received by a built-in RS-232 port. The program time stamps each data packet as received and logs the Eyespy information to a separate text file. All logged data are displayed in real time in an appropriate format to the user as either stripchart traces or simple counter displays, as shown in the graphical user interface screenshot, Figure 10.

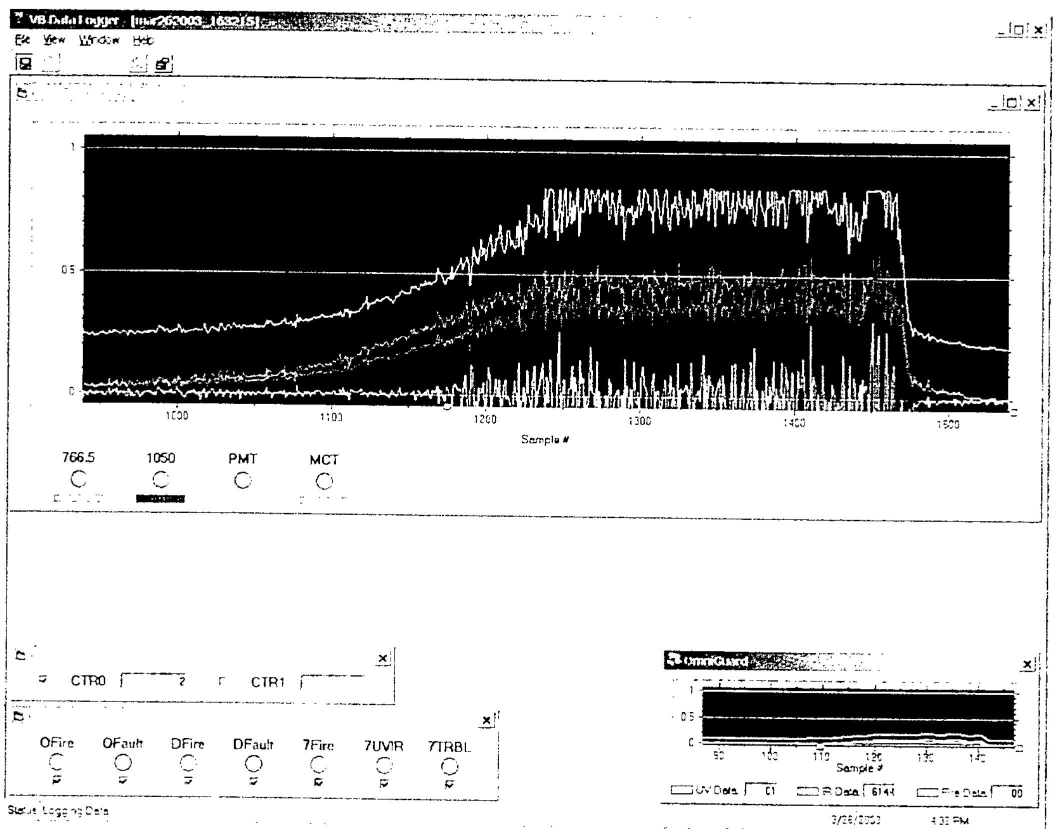

Figure 10. Graphical user interface for the data logging program used to acquire and store data from the SBVS Testbed

PRELIMINARY TESTS: HOOD FIRES

Initial testing of the testbed sensor suite and DataLogger program was carried out for several small fires in a fume hood at NRL. The sources were heptane (1 inch diameter pool), balls of tissue paper, and potassium chloride/methanol. The sensors were positioned as shown in Figure 11 and placed about 10 feet from the fume hood and about 3 feet from the floor (near to the height of the fires). The test fires

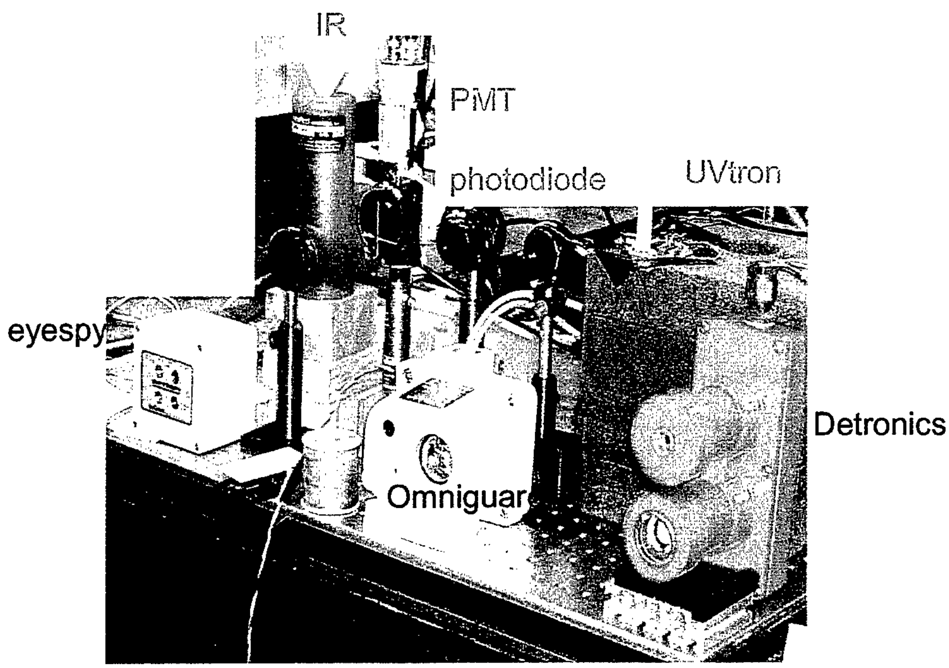

Figure 12. OFDs and in-house detectors that comprise the spectral sensor testbed

were also recorded with both the Sony camcorder in Nightshot mode and the bullet surveillance where 720 nm long pass filters were used for each. Table 2 list the fire sources, root testbed file names, ignition and flame disappearance times and tape exposure time for the videos recorded.

Table 2. Hood fires used in preliminary tests of the spectral testbed

Fire source	Data file[a]	Ignite		Flame out	
		Real	Camera[b]	Real	Camera[b]
Heptane	153923	155037	15:27	155313	18:02
Paper	155229	160009	23:19	160140	24:50
		160207	25:14	160349	26:56
KCl/Methanol	161208	161948	29:00	162253	32:05
Paper	162038	162809	35:30	163049	38:10

a. The datafile root name includes the data logging initiation time (in 24 hour time). The first part of the root file name is the date, which has not been included in the table since it is the same for all those listed. For example, the data file name for first fire is Apr102003_153923.x. The suffixes ("x") for the analog (and frequency) data, omniguard and eyespy data are "dat", "omni" and "spy", respectively.

b. Elapsed time on Sony DVM60 tape.

The testbed response for the fires in Table 2 are shown in Figures 12-14. Each figure consists of four plots. This first shows the output from the in-house sensors; these include visible region silicon photodiodes at 766 and 1050 nm, the potassium emission sensor and a guard band, as well as the UV PMT 308 nm and IR MCT 4.3 μm sensors. The second plot shows the output from the alarm relay for the Omniguard, Eyespy, and Det-tronics flame detectors. The Eyespy is the only OFD with non-latching alarm relays, so the relay resets during the course of the experiment and often exhibits multiple alarm events. The third plot is for the output of the Omniguard flame detector, including IR (identified as Ref IR) and Fire, where the latter is a combination of IR and UV as noted above. The fourth panel displays the Eyespy OFD outputs. In some cases, such as for several flame detector channels and for the PMT output, the nonzero background signal was subtracted. The MCT signal was rectified and smoothed. Several signals, e.g., UV channels, were scaled up to more easily display them with the other data. The scaling is noted in the legend for each channel.

In each of the fires shown, all of which exhibit substantial flames, there is an alarm relay from the flame detectors. In each case the Eyespy alarms after the other two flame detectors. The Det-tronics trips first in the heptane fire (with the Omniguard in a few seconds after) and the Ominguard relays first for the other two tests. The largest delay between OFDs is for the paper fire for which the Ominguard alarms first, the Det-tronics 20 seconds later, and the Eyespy 15 seconds after that. Some of this could be in the sensitivity setting as the individual elements appear to respond at nearly the same time. In smaller (paper) fires, the Omniguard went off while the other two did not.

There is clearly a healthy response from the in-house detectors depicted in the top panels for each run. The signal magnitudes of the in-house detectors, e.g., of the PMT vs. the other in-house detectors, are somewhat artificial since they reflect the detector gain and not necessarily the detector signal-to-noise ratios. The UV (PMT) and IR (MCT) sensors response in each case occurs on a time scale similar their counterparts on the OFDs. The relative response from the various sensors, especially for the photodiodes, for the different fires are consistent with the spectra measured for each type of fire, which are described above. In particular and as might be expected, the potassium salt containing source resulted in a stronger signal for the 766 nm photodiode than for the 1050 nm sensor, whereas for the other fires the two photodiodes yielded comparable responses. Each fire lasts about 2-3 minutes, and once the flames are gone, the signals from the sensors return to their baselines. The preliminary tests of various hood flaming fires indicate that the testbed sensors are responsive and ready to be evaluated in a wider range of fire scenarios, such as the April 2003 ex-USS *SHADWELL* tests.

PLANNED TESTS ON EX-USS *SHADWELL*

There are two series of tests planned for April, 2003 to be carried out aboard the ex-USS *SHADWELL*. The first is the CVNX Test Series (7-18 April) which will be followed by the Volume Sensor 1 Test Series (21-25 April) . The former includes relatively large fires as described in the test plan [21]. Some instruments from the VS Program will be tested during the CVNX tests. These include several video fire systems and several detectors operating outside the visible region from the SBVS effort. The SBVS units to be deployed OFDs (UV/IR Omniguard 752) as well as nightvision cameras. Tests are to be conducted in two compartments, the second deck, small magazine and the third deck, medium magazine. One OFD is mounted on the wall of each compartment. The relays (and power) are monitored (and provided by) the EST panel that also monitors the collection of COTS smoke and heat detectors. Nightvision cameras are mounted next to and pointing in the same direction as the video cameras. There are two in each compartment, but we have used different kinds of cameras and filters. The second deck, small magazine includes a Sony camcorder (with its illuminator on) in the starboard, aft position and a bullet camera in the port position. Both have 720 nm long pass filters. In the third deck, medium

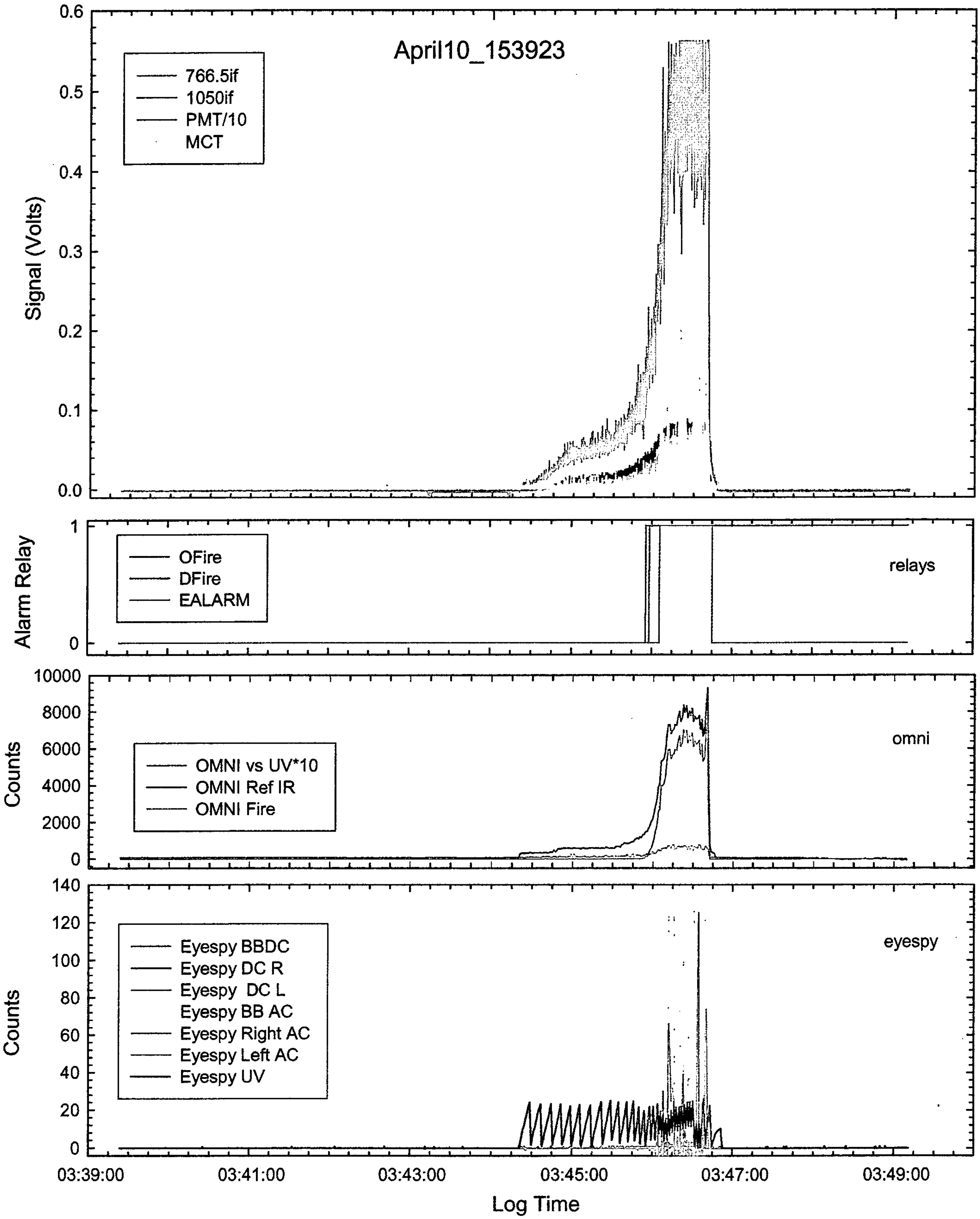

Figure 13. Testbed results for a heptane fire

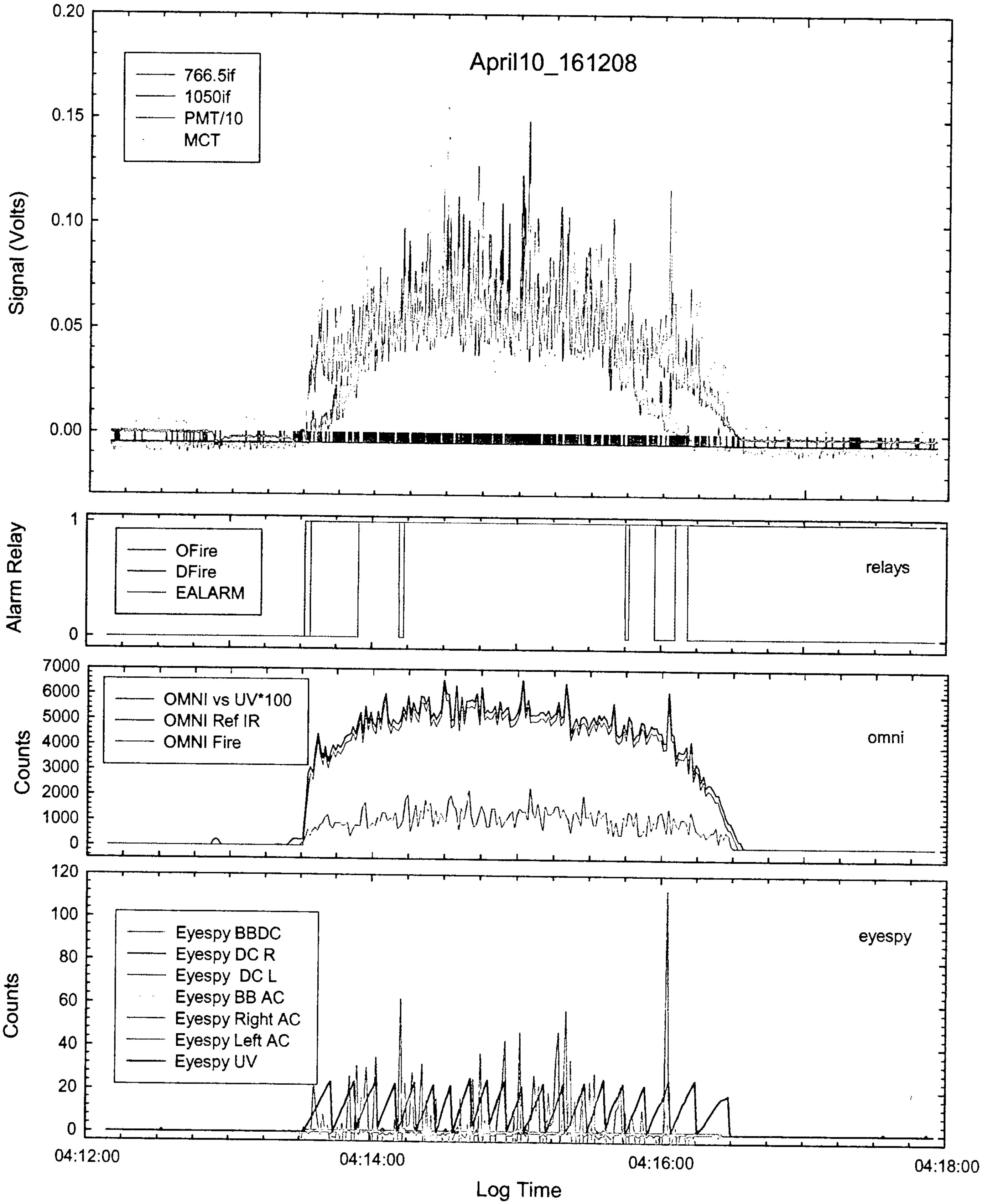

Figure 14. Testbed results for a paper fire

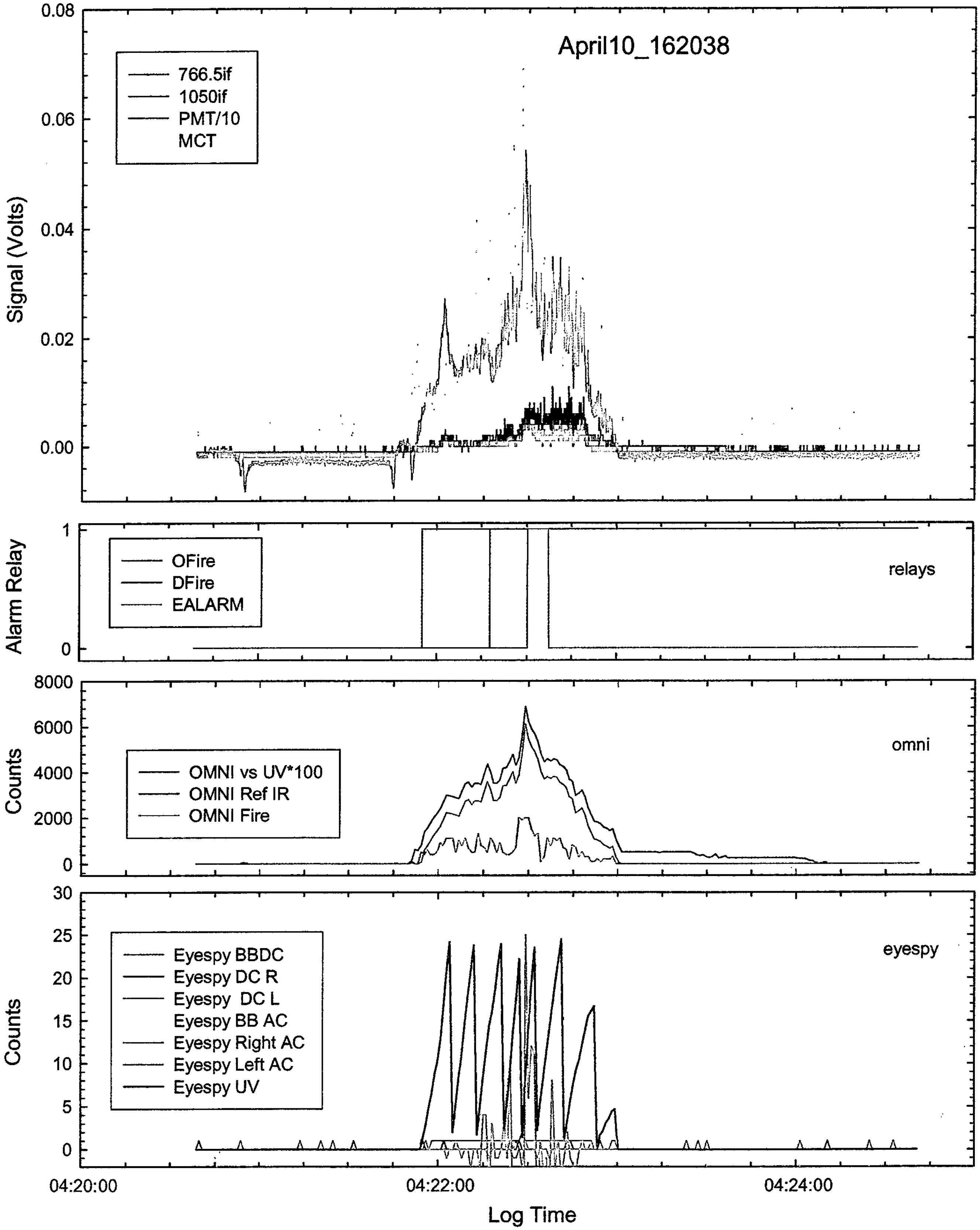

Figure 15. Testbed results for a potassium chloride/methanol fire

magazine, both cameras are bullet cameras; the starboard one has an 850 nm filter and the port has a 720 nm filter. Schematics of the magazine indicating the camera locations are available in another report [22]. The nightvision videos are being recorded on VHS video cassettes with a time/date stamp overlay applied to the image prior to recording.

For the VS test series on the ship [23], the fires are more modest and they will be monitored not only with the cameras (video and long wave) and OFDs, but also with the Spectral Testbed. The test fires (and spectra of them) have been described above; Nuisances are also planned, such as cutting and welding steel and waving towels. The results will be described in a forthcoming report.

SUMMARY

The progress to date, leading up to the April 2003 ex-USS *SHADWELL* Test Series, has been described for the SBVS program. The two promising routes of nightvision imaging and narrow band spectral detection are being pursued to complement video fire detection that is being developed as the primary thrust of the VS Program. A Spectral Testbed has been configured, constructed, and subjected to initial testing. It includes various narrow band single element detectors operating outside the visible region and is comprised of diagnostic mode OFDs as well as in-house constructed sensors. In preliminary tests, almost all the various testbed sensors clearly responded such that it would be straightforward to establish an alarm threshold and use them as fire or flame detectors. Although they would benefit from more quantititative sensitivity and interference studies, it will be useful to evaluate the sensors over a wider range of circumstances in the upcoming shipboard tests.

Filtered, long wavelength videos were recorded for several small hood fires and indicate that this approach is capable of providing a high degree of discrimination for flame, fire, and hot objects, including reflected fire emission. Being able to sense reflected radiation is important for an optical fire detection system since one potential drawback is that the entire volume may not be in the direct line of sight of the detector(s). The results of the upcoming tests should demonstrate the benefits of nightvision fire detection.

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